A holistic approach to the atom in school chemistry

Un enfocament holístic a l'àtom en la química escolar

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abstract

Many curricula and syllabi have been developed to foster meaningful understanding of the atom. Yet, the atom remains a difficult concept for many students. In this article, it is argued that a shortcoming in science teaching and learning of science concepts, including the atom, include limited coordination among (*a*) the various forms of scientific knowledge, and (*b*) the epistemic, cognitive and social aspects of scientific practices. Visual tools that can be helpful in communicating the complexity of various aspects of science are also presented.

keywords

Atom, nature of chemistry, growth of chemical knowledge.

resum

Molts plans i programes d'estudi s'han desenvolupat per fomentar la comprensió significativa de l'àtom. No obstant això, l'àtom segueix sent un concepte difícil per a molts estudiants. En aquest article, s'argumenta que una deficiència en l'ensenyament de la ciència i l'aprenentatge de conceptes científics, inclòs l'àtom, inclouen la coordinació limitada entre (*a*) les diverses formes de coneixement científic i (*b*) l'epistèmica, aspectes cognitius i socials de les pràctiques científiques. Es presenten eines visuals que poden ser útils en la comunicació de la complexitat dels diversos aspectes de la ciència.

paraules clau

Àtom, naturalesa de la química, desenvolupament del coneixement químic.

As this volume of *Educació Química EduQ* and many other resources worldwide illustrate, the atom is a central concept in the teaching and learning of chemistry. Substantial number of studies have been carried out on students' conceptions and misconceptions about the atom. Many curricula and syllabi have been developed to foster meaningful understanding of the atom. Why is it, then, that there still is a significant problem in students' understanding of the atom? Why is it that even students in higher education experience difficulties in conceptualizing the atom? What is missing in all the countless efforts to improve the teaching and learning of the atom?

I want to argue that a shortcoming in science teaching and learning efforts include limited coordination among (*a*) the various forms of scientific knowledge, and (*b*) the epistemic, cognitive and social aspects of scientific practices. By forms of scientific knowledge, I refer to theories, laws and models. By scientific practices, I refer to those practices that lead to the generation, evaluation and revision of scientific knowledge. In our recent book on the reconceptualization of nature of science in science education (Erduran & Dagher, 2014), we have argued that there is often very little effort placed on helping students understand science in a holistic fashion. This is true of both scientific knowledge and scientific practices. In our work, we provided a theoretical rationale drawing from work on philosophy of science to illustrate how nature of science can be represented and presented in school science in a holistic fashion, ranging from the aims and values of science to the social-institutional contexts of science. For various aspects of science, we then provided a set of visual tools referred to as *generative images of science*. These images, which will

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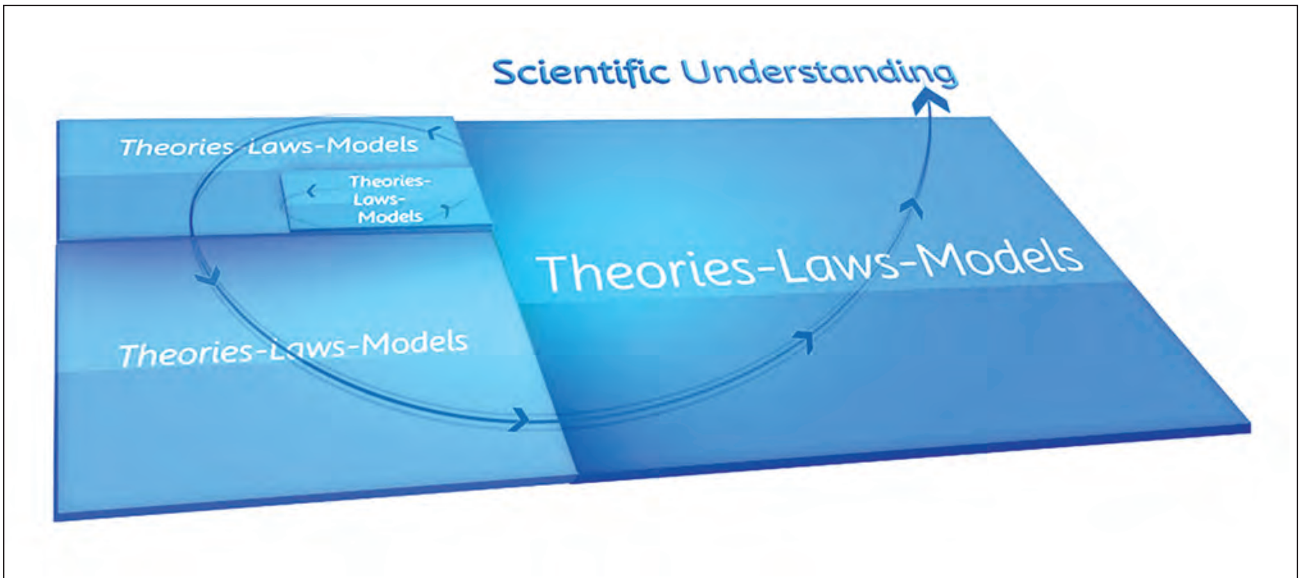

Figure 1. Theories-laws-models, growth of scientific knowledge and scientific understanding (Erduran & Dagher, 2014, p. 115).

be exemplified in the rest of this paper, are generative because they can lead to further articulations both conceptually and pedagogically.

Let me start with the issue of scientific knowledge and illustrate how the discussions on the teaching and learning of the atom could benefit from how we envisage the coverage of scientific knowledge in a holistic way. Theories, laws and models work together in the growth of scientific knowledge. Often, school science presents different forms of scientific knowledge without articulating them coherently let alone discussing the relationships between them. If we take atom as an example, this means that even though the atomic theory, the atomic model and periodicity as a pattern in elements are introduced to students, there is hardly ever any indication of how these forms of knowledge are about or how they interact in leading to understanding the structure and function of matter. For example, what is the relationship between the atomic «theory» and the atomic «model»? Are there law-like regularities that contribute to our understanding of the atomic model and how are they related to what makes a model?

Consider fig. 1, which communicates how theories, laws and models (referred thereafter as TLM) operate within a particular tradition in a coherent and interrelated fashion.

Altogether, TLM brings coherence to the various forms of scientific knowledge, illustrate how they are related and also account for how TLM grows as evidence accumulates. If you consider each quadrant of the figure, theories, laws and models are related in a particular topic like the atom in a coherent way. TLM grows in time as evidence accumulates leading to scientific understanding at every stage. However, there may be points in time when the TLM are no longer able to account for the evidence observed and hence, a new set of knowledge forms are needed, leading to a new paradigm, referred to by Thomas Kuhn as a «paradigm shift». A new paradigm could be represented as a new «plane» where the knowledge accumulation process begins and continues.

In our work, we have represented TLM and growth in TLM visually. We can take the example of the atom. Each stage in the formulation of chemical understanding around the atom can be represented by a separate plane, for example the ancient Greek depiction of four elements (earth, water, fire, air) and Lavoisier's conception of elements would constitute separate «planes» that have represented knowledge accumulation over time. When TLM couldn't account for observed evidence and the entire paradigm had to change, scientists begin to formulate a new plane of knowledge. Kuhn himself used the example of atomic theory to illustrate the concept of *incommensurability* (Kuhn, 1970, p. 85) meaning that different par-

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adigms would not map onto each other due to their fundamentally different paradigmatic assumptions. The change from properties of matter such as colour to quantitative analysis of reactions could not possibly be mapped to the same knowledge plane. The broader theoretical framework, the regularities and patterns in the behaviour of matter and the representations of properties or reactions worked in unison to provide an overall paradigm.

A key shortcoming of school chemistry is that the curriculum does not represent the atomic theory to students in relation to the associated models and laws, or how they possess explanatory and predictive power that leads to chemical understanding. Rather, students are typically introduced to disparate pieces of knowledge (*e.g.* «the atom consists of a nucleus and electrons») that are essentially data points on each quadrant of fig. 1. Whenever knowledge from different paradigms are presented (*e.g.* Dalton's vs. Bohr's atom), there is rarely any lead into the historical conditions, criteria and standards that actually made the progressions in knowledge growth and revision necessary. From the students' point of view, shifts in the TLM growth or revision remain a mystery.

How, then, could heuristics such as the one represented in fig. 1 help students in understanding the atom? First, the heuristic is a «meta-tool» that highlights the significance of understanding what constitutes chemical knowledge. Without a sense of differentiation of theories, models and laws, all information that is presented to students is of the same epistemic value. In other words, while we recognize from the work of philosophers of chemistry that various forms of knowledge have different characteristics, these are mostly undifferentiated in school chemistry. Such ambiguity presents problems for an authentic representation of chemical knowledge in school chemistry. If we are serious about promoting student understanding of chemistry, then a meta-level appreciation of what constitutes chemical knowledge is not a luxury. It's a necessity. Second, the heuristic gives learners a sense of the progression of ideas, how ideas change over time and how ideas can at times be abandoned altogether in favour of new ones. Hence, students begin to develop an understanding of how scientific knowledge growth works.

We can also question how these theoretical ideas can be implemented in actual chemistry lessons. The TLM heuristic can be used to generate a set of instructional sequences that places a strong emphasis on articulating the relationships between theories, laws and models. Apart from some generic discussions about such relationships (*e.g.* what's the difference between a theory and a model?), specific discussions can take place in reference to the atom (*e.g.* is the atomic theory the same thing as the atomic model?). Questioning and discussion can play a significant role in eliciting rich coverage of not only the meta aspects of chemical knowledge but also by drawing in the particular concepts and organising them in a coherent whole, students' conceptual understanding might also be reinforced.

Let me now turn to a brief discussion of scientific practices which underlies the processes that lead to the generation of scientific knowledge. Scientific practices such as experimentation, observation and classification all contribute to how scientists generate data. Scientists use data to build models which can be used to predict phenomena. These epistemic practices of knowledge construction happen through the mediation of cognitive and social practices such as reasoning, argumentation and social certification of ideas. We have produced a visual tool that we refer to as the *benzene ring heuristic* where we consolidate, in a relatively simpler fashion, the various epistemic, cognitive and social aspects of science that lead to the production of scientific knowledge. Consider fig. 2, that uses the analogy of the benzene ring to summarize scientific practices. Each carbon atom around the ring and the diffuse π bonds represent the social contexts and practices that apply to all of these aspects. The cognitive, epistemic and social aspects of science are interrelated and influence one another. The ring structure represents the «cloud» of cognitive and social practices that mediate the epistemic components such as models and explanations.

The benzene ring heuristic begins to articulate how scientists use data originating from the real world to generate models, explanations and predictions. In a sense, the heuristic highlights the mechanisms for how the TLM growth occurs. In school chemistry, the activities of experimenta-

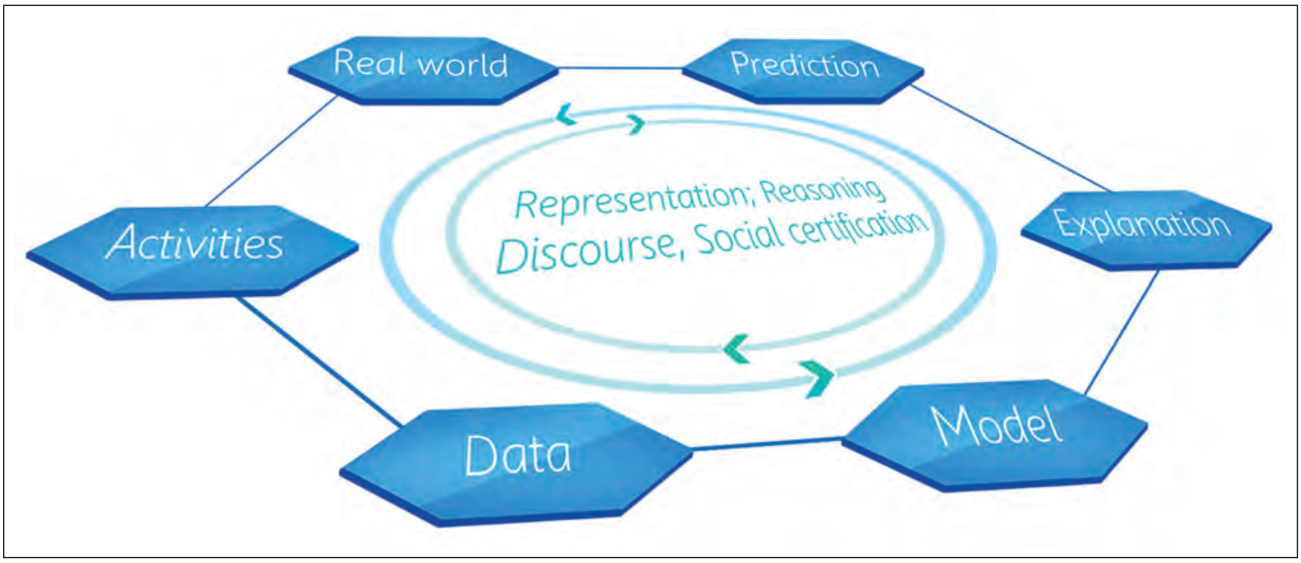

Figure 2. Benzene ring heuristic of scientific practices (Erduran & Dagher, 2014, p. 82).

tion, classification and observation tend to be covered in a disconnected fashion that don't necessarily lead to modelling practices by students themselves. What the heuristic aims to foster is a coordinated approach to how students can be helped in understanding how the various practices of science are interrelated. For example, chemists debate what data to use to generate models and how. The epistemic dimensions of such discussions are intertwined with social processes of debate and representations. In short, while fig. 1 emphasizes the components of scientific knowledge and its growth, fig. 2 illustrates some of the mechanisms and interactions that underlie and underscore how the various forms of scientific knowledge need to be coordinated in a finer level of detail. The benzene ring heuristic can be used to get the students to think about, for instance, how a model of the atom is related to the «real world» or how the atomic model can help predict chemical behaviour. Our recent work indicates that the use of the benzene ring heuristic in teacher education can help improve pre-service science teachers' conceptualisation of scientific practices from simple linear representations to more complex and holistic representations (Erduran, 2014). Overall, the visual tools are generative in helping guide the discussion of various aspects of scientific knowledge and practices. In summary, a holistic approach to the knowledge and practices underlying the development of the «atom» is likely to facilitate students' understanding because it will consolidate the often fragmented aspects of chemistry in school chemistry into meaningful and interconnected set of ideas.

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